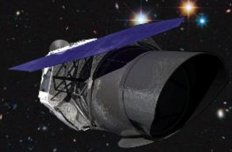
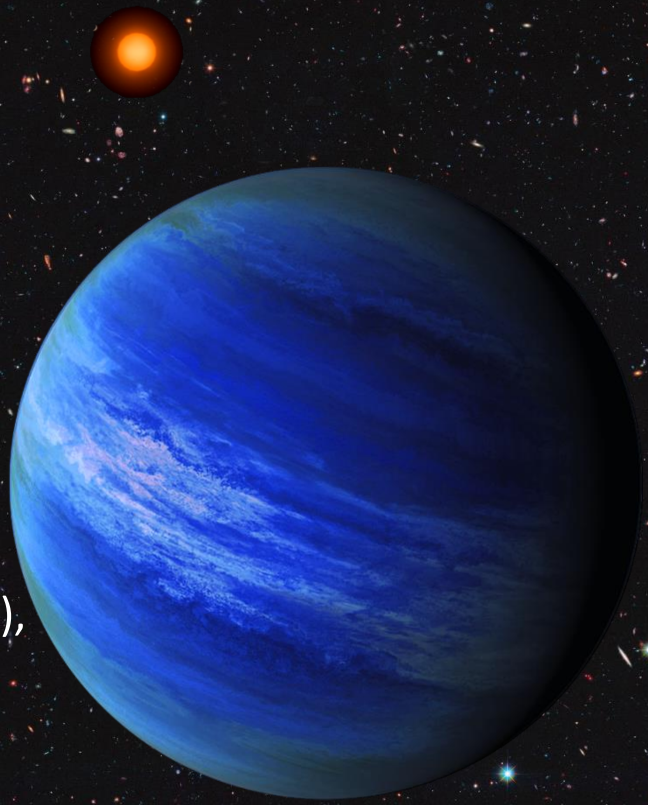


Coronagraph Design for the WFIRST CGI



A J Eldorado Riggs

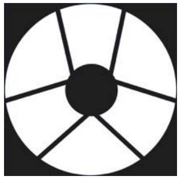
Optical Engineer

Jet Propulsion Laboratory,
California Institute of Technology

Garreth Ruane (Caltech), Neil Zimmerman (GSFC),
Dwight Moody (JPL,Caltech), John Trauger (JPL,Caltech),
Bijan Nemati (UAH), John Krist (JPL,Caltech)

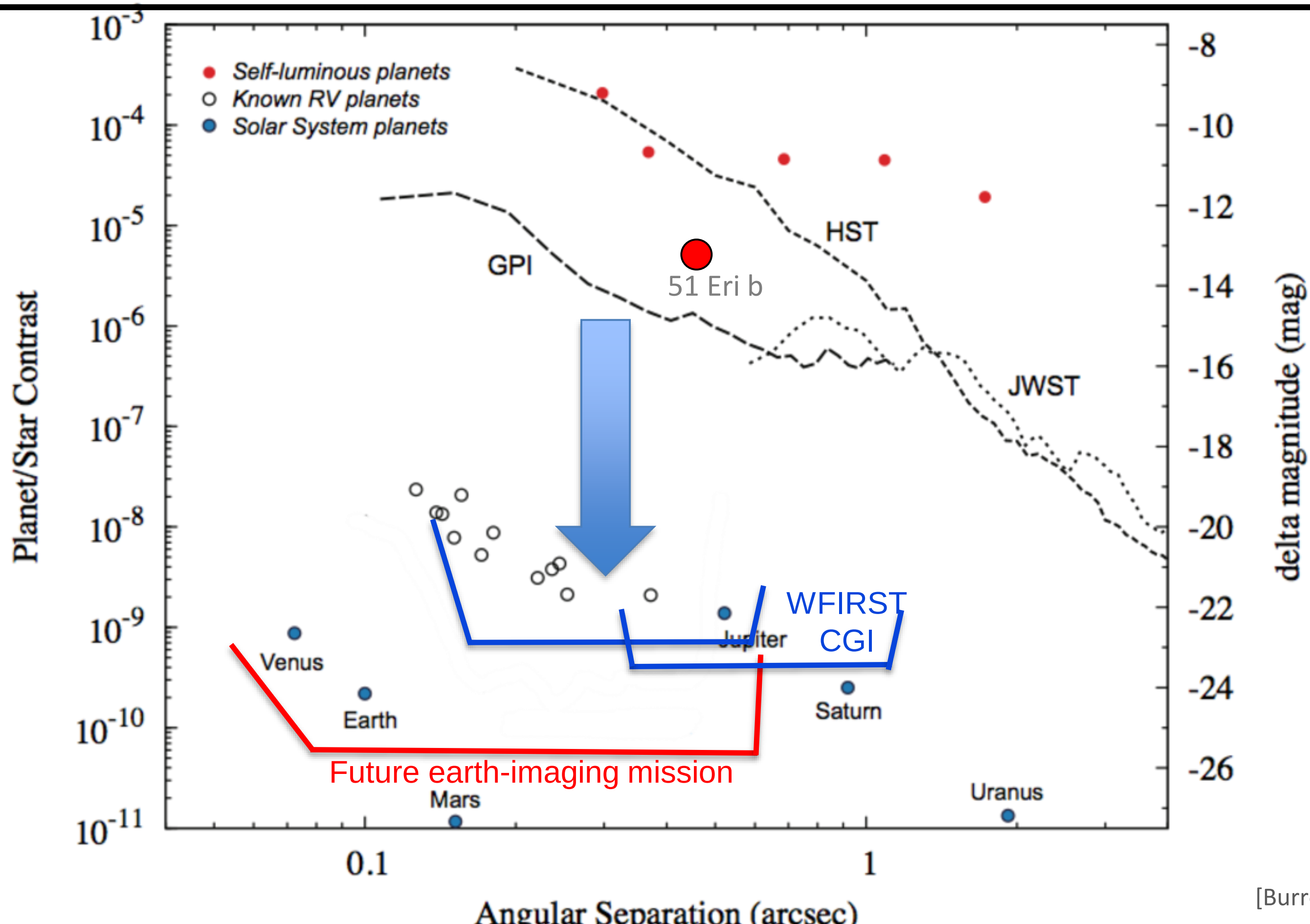
ExSoCal 2017 Meeting
September 19, 2017

Current and Future Observatories



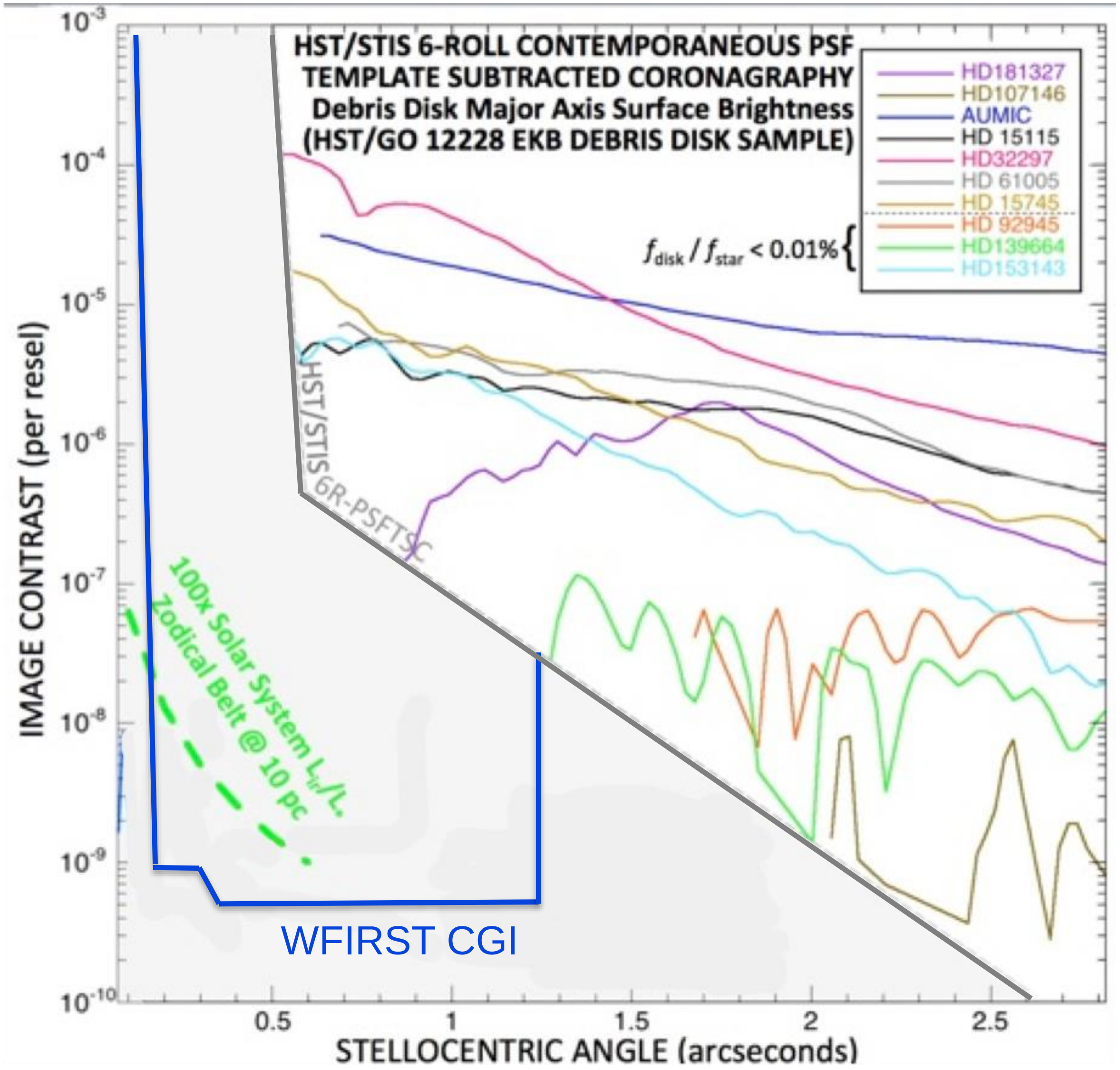
WFIRST Coronagraph Instrument (CGI)

- Launch in 2026
- ≈10^{-9} raw contrast from 150-1200 mas
- Visible-light imaging and spectroscopy for cold gas-giant exoplanets & inner debris disks



[Burrows 2014]

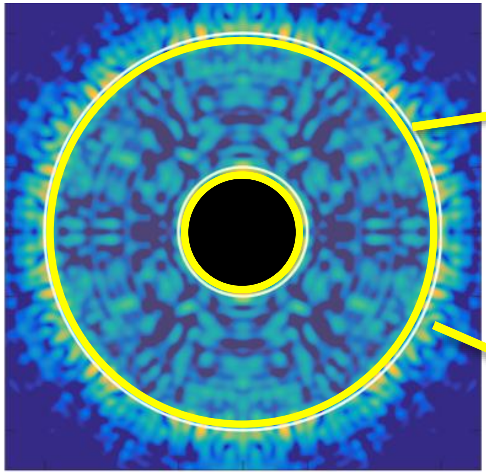
New Disk Science with WFIRST



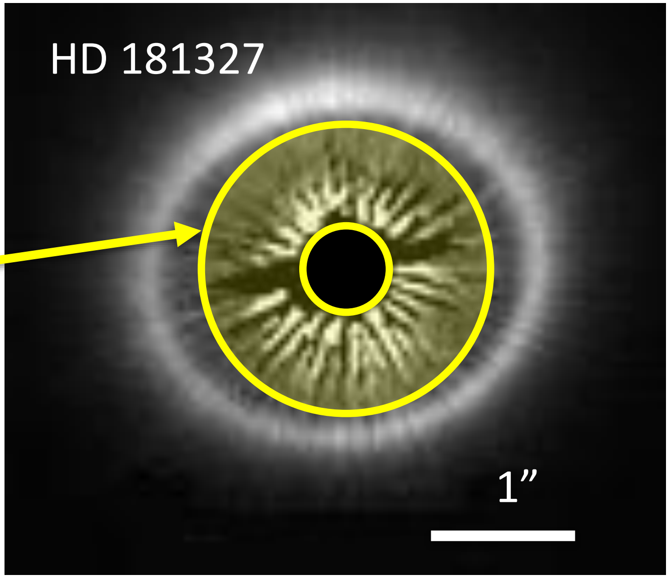
[Scheider 2014]

Disk Science

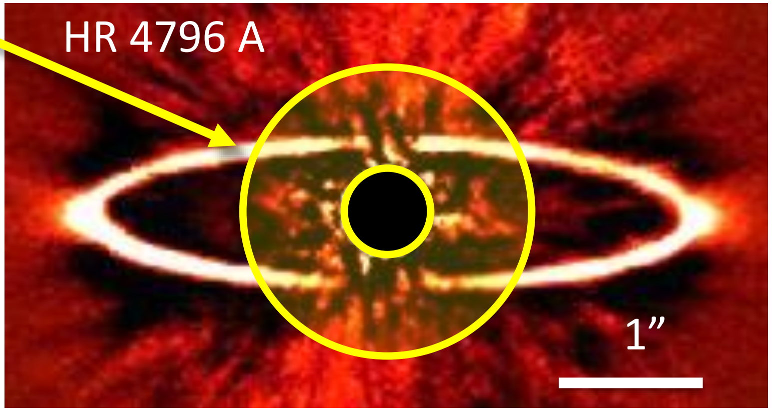
WFIRST CGI



HST STIS



VLT SPHERE



- 1.9” FOV in V band
- 10% spectral bandwidth
- ~10^{-9} raw contrast

Coronagraph Design

Goals:
- **Maximize the science yield.**
- **Minimize risk.**

Design Parameters

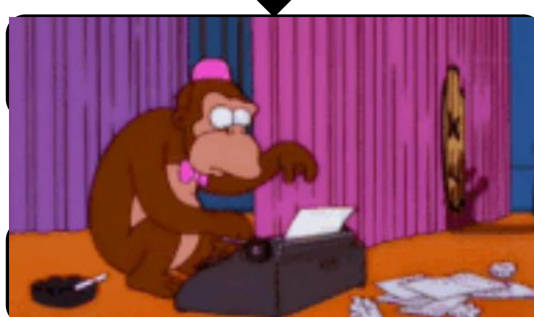
Sensitivities to:
- **Pointing jitter**
- **Wavefront jitter** (coma, astig, focus)
- Primary mirror **polarization**
- Mask **misalignment**

Performance Metrics
- **Contrast**
- **Throughput**
- Spectral **Bandwidth**
- **Field of View** (IWA, OWA, angle)

Mask Properties
- Mask **shapes**
- Mask **materials**

Coronagraph Optimizer

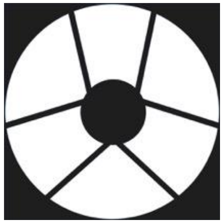
Masks



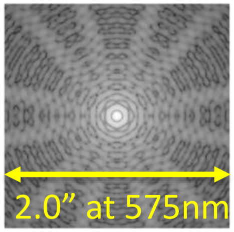
contrast, etc.

Types of WFIRST CGI Mode

WFIRST pupil

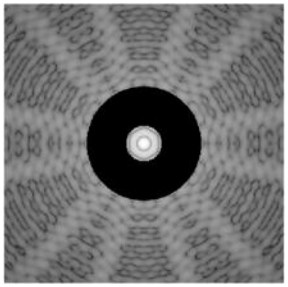


Nominal PSF

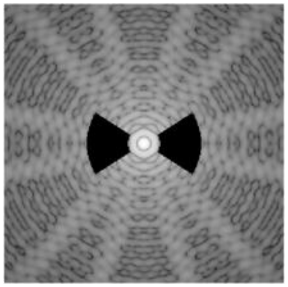


- **3 modes** to achieve science goals:

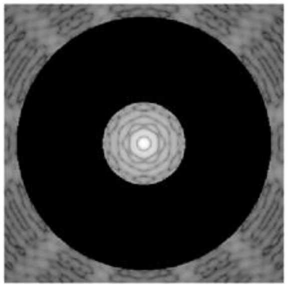
(Notional dark holes)



1. **Hybrid Lyot Coronagraph (HLC):** *exoplanet & inner disk imaging*
   - 10% BW, 360º FOV, 3-10 λ_0/D
   - ~4% core throughput



2. **Shaped Pupil Coronagraph (SPC)** for IFS: *exoplanet spectroscopy*
   - 18% BW, 2x65º FOV, 2.8-8.8 λ_0/D, lower sensitivities
   - ~4% core throughput



3. **Shaped Pupil Coronagraph (SPC):** *outer disk imaging*
   - 10% BW, 360º FOV, 5.5-20 λ_0/D
   - 5.5% core throughput

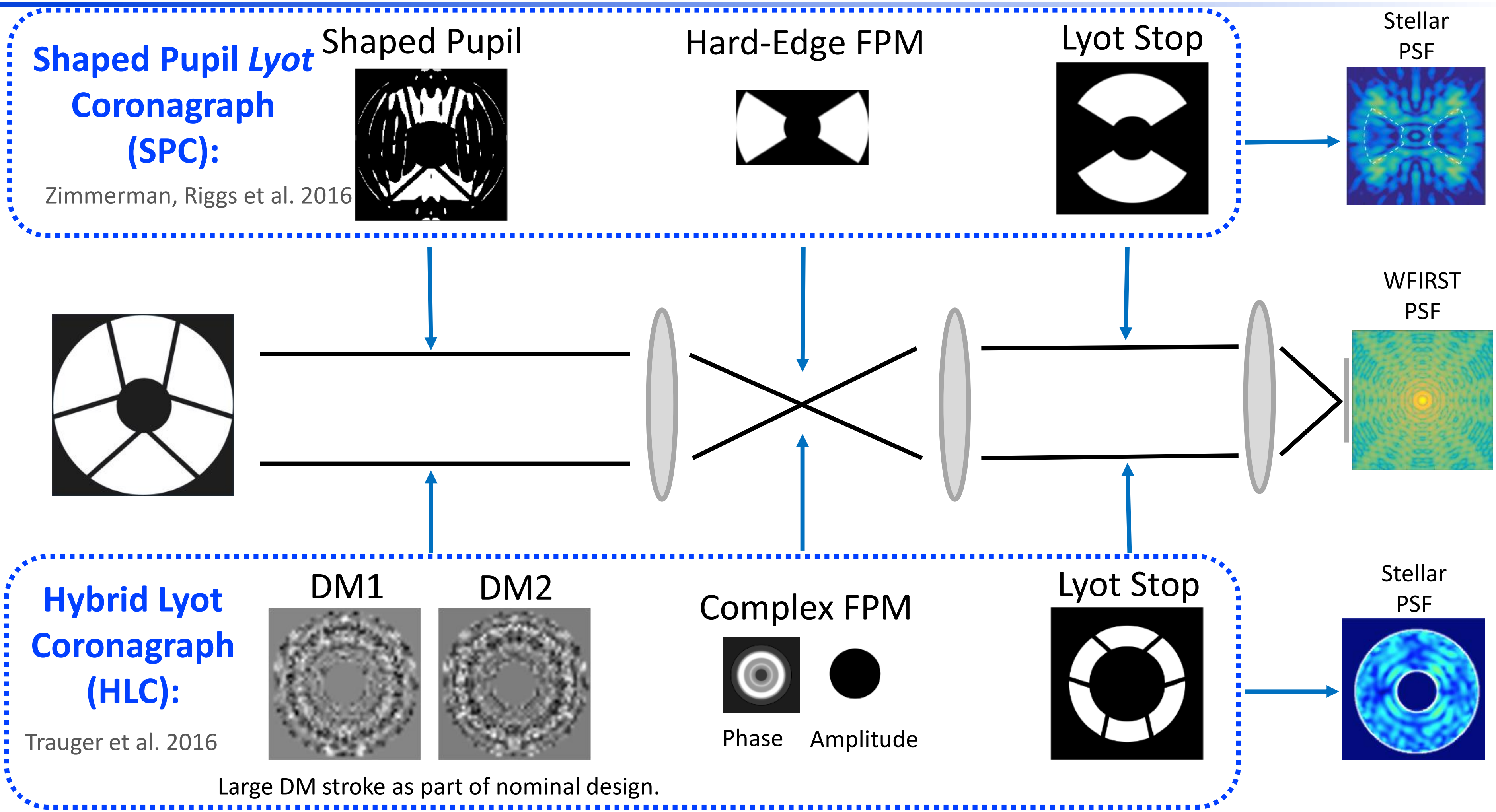
- Trauger et al. JATIS 2016
- Riggs SPIE 2014
- Zimmerman, Riggs, et al. JATIS 2016

Coronagraph ?

Chronograph

Jet Propulsion Laboratory
California Institute of Technology

The WFIRST Coronagraphs



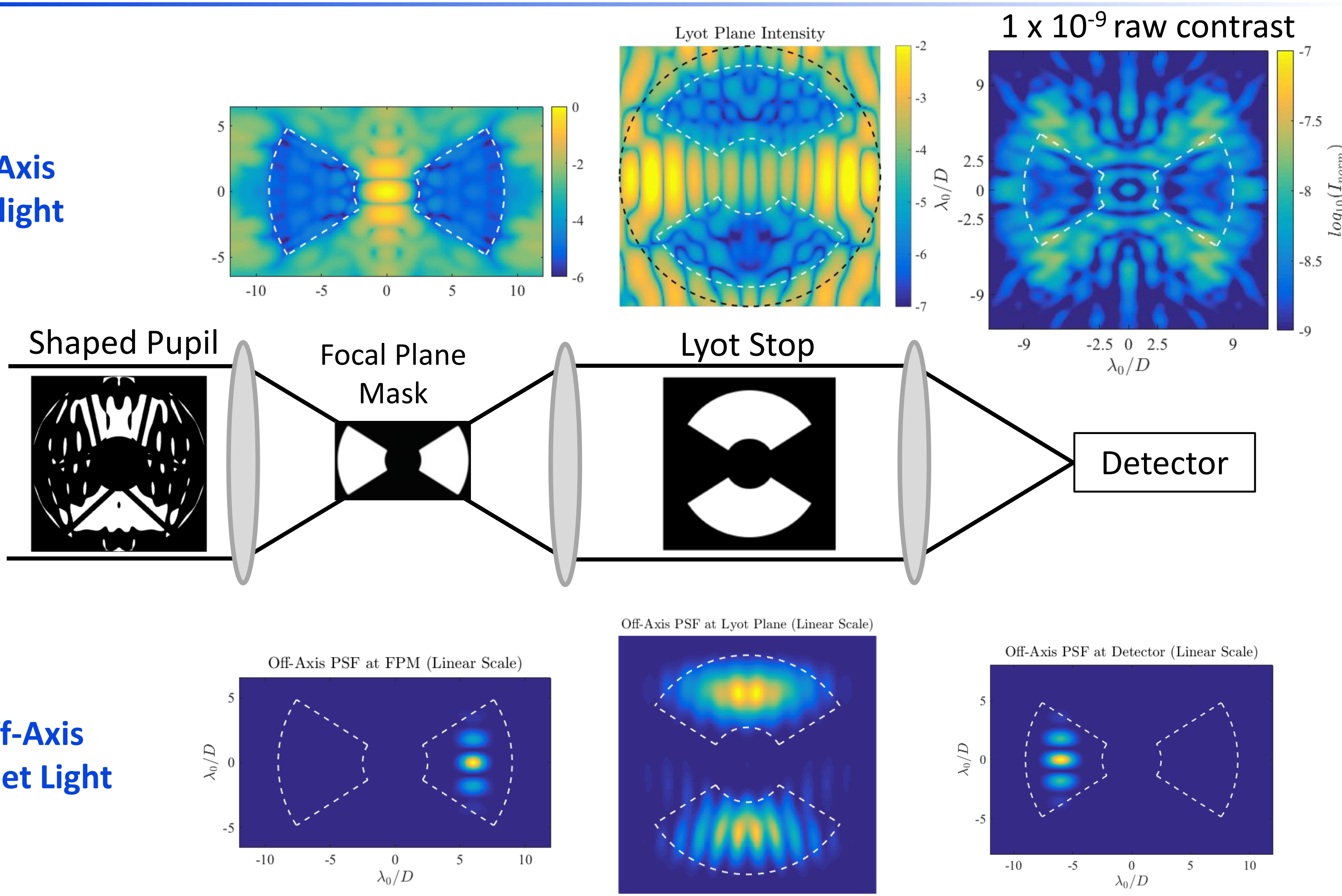
Benefits of Each Coronagraph (complementary):

- HLC: Full **FOV**, fewer masks, easier **alignment**
- SPC: Broader **bandwidth**, better aber. **sensitivities** (esp. **PM pol.**), lower risk with DMs

Shaped Pupil Lyot Coronagraph

On-Axis Starlight

Off-Axis Planet Light



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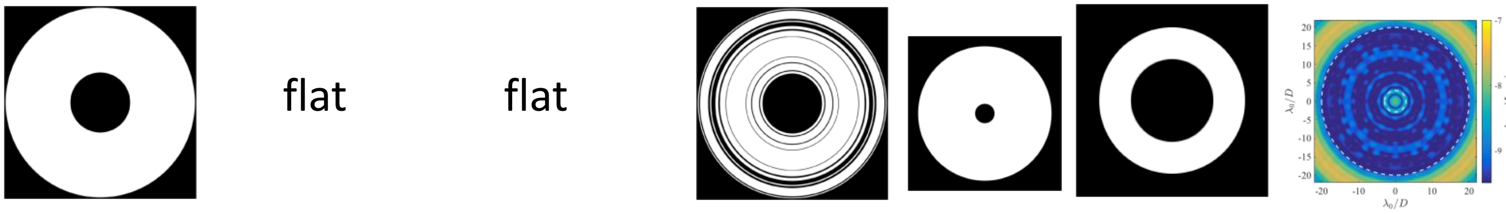
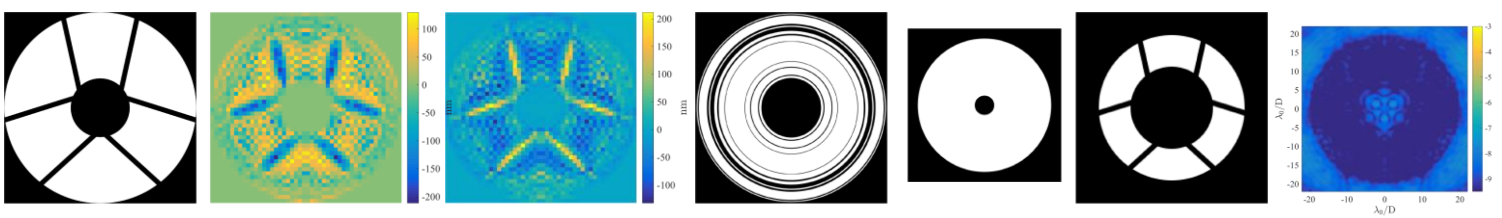
Ongoing Work: Hybridized Designs

Pupil	DM1	DM2	Shaped Pupil	FPM	Lyot Stop	Stellar PSF



4 x 10^{-10} contrast
9.6% throughput
3.1 -19.7 λ/D
10% bandwidth

Step 1: Perform grid search to find best 1-D radial solution.



4 x 10^{-10} contrast
~5% throughput
3.1 -19.7 λ/D
10% bandwidth

Step 2: Use DMs to suppress diffraction from struts.

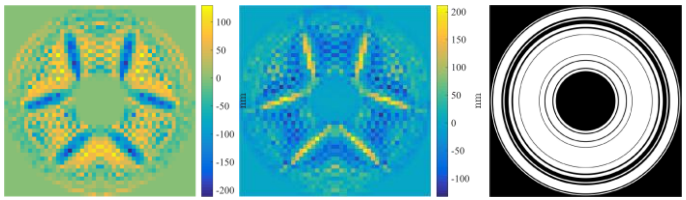
DMs mitigate the struts' diffraction more efficiently than the shaped pupil mask
- Better achievable throughput, IWA, and/or contrast

[*For related work, refer to* Mazoyer et al. 2017]

Summary

- WFIRST CGI will revolutionize direct imaging
  - First cool exoplanet images and spectra
  - First visible, scattered-light images of exozodiacal dust
  - First high-contrast coronagraph in space with active optics

- Design work is focused on
  - New numerical design methods
  - Increasing science yield
    - Improving performance and robustness



Backup Slides

HLCs for Future Telescopes

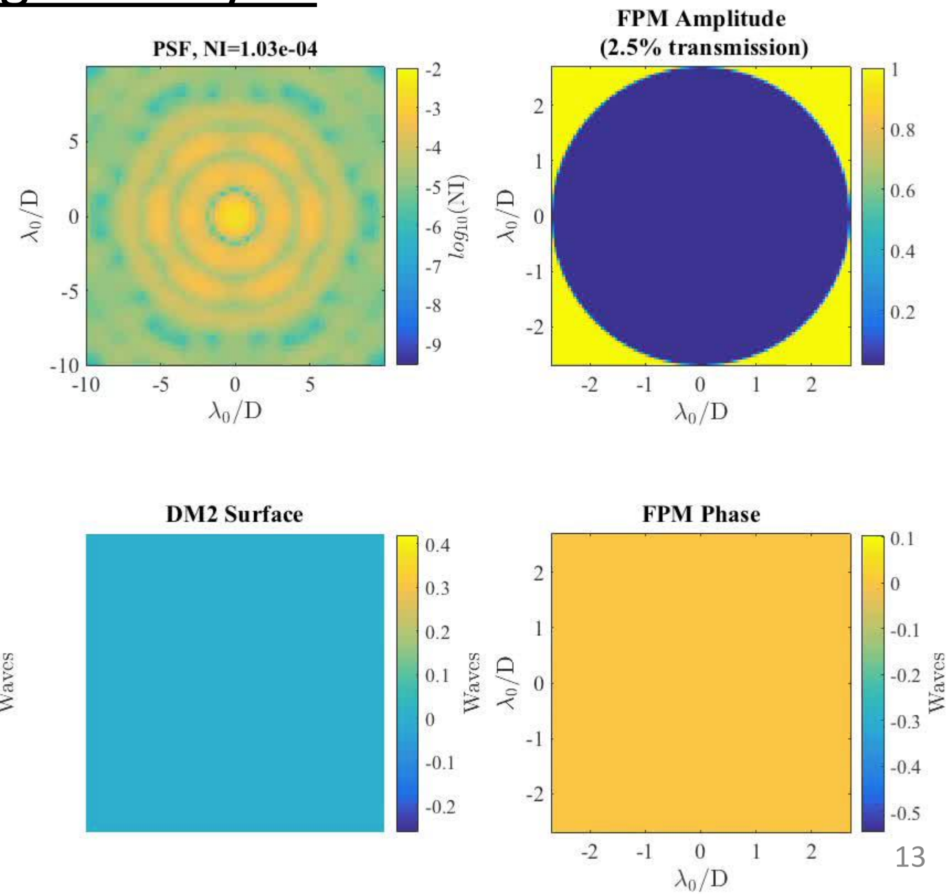
- The future of coronagraph design is **numerical optimization**.
    - Because of sensitivities and obstructed pupils.
- Hybrid Lyot Coronagraphs (**HLCs**) are
    - Manufacturable
    - High performance
    - Tunable
- Need a **fast code** for HLC design surveys…

FALCO:
FAst
Linearized
Coronagraph
Optimizer

Iteration 0

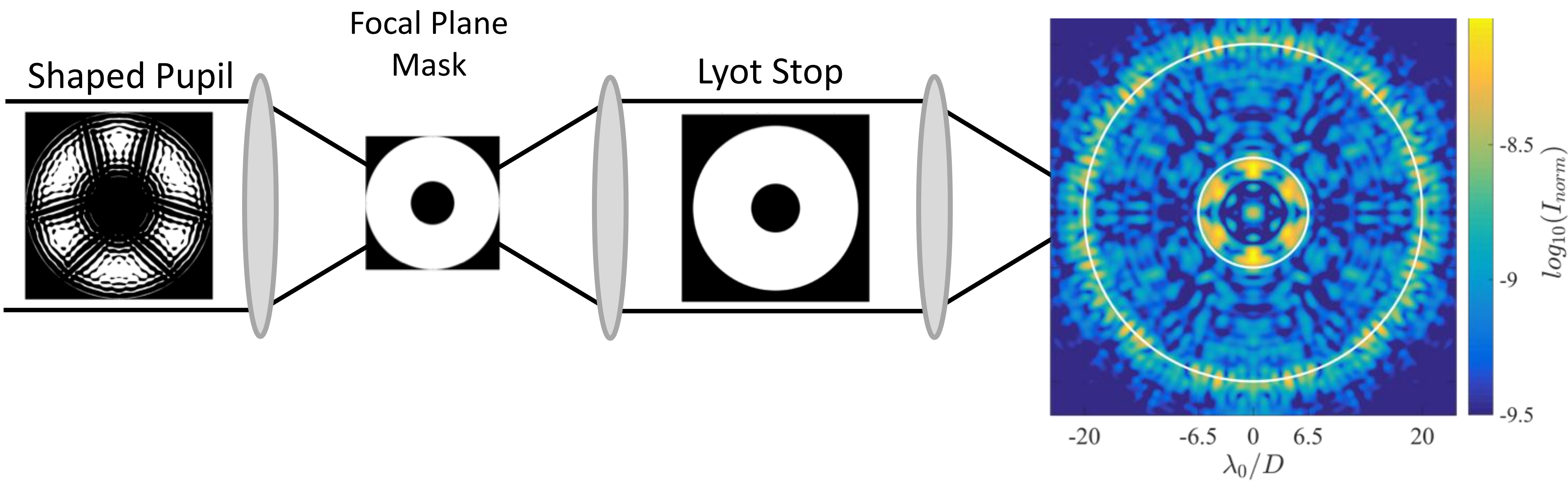
NI = 1.03e-04

10% Broadband



SPC-Disk Science Design

2017 Design A



Specs:

- **6.5 x 10^{-10}** contrast ***(5x better)***
- r=0.33-1.0" FOV (in V band)
- 10% Broadband
- Core throughput = 5.5%

Planned Design Pipeline

1) SPLC-IFS Optimization Code

Python wrapper

Done

Grid search over design variables.

AMPL base code

Masks from each design

2) Rapid Optical Simulator (MATLAB)

Simulate effects of:

Nearly Done

1) Tip/tilt: jitter and stellar size

2) Differential **polarization** wavefronts.

3) [*Later*] **Empirical fudge factor**
   - From empirical (Monte Carlo) simulations of misalignments & aberrations.

Tables: Raw contrast, throughput, core area

3) Bijan's RV Planet Exposure Time Calculator (MATLAB)

Nearly Done

Vary input planet parameters.

Exposure times & # of Spectra

4) Human Review

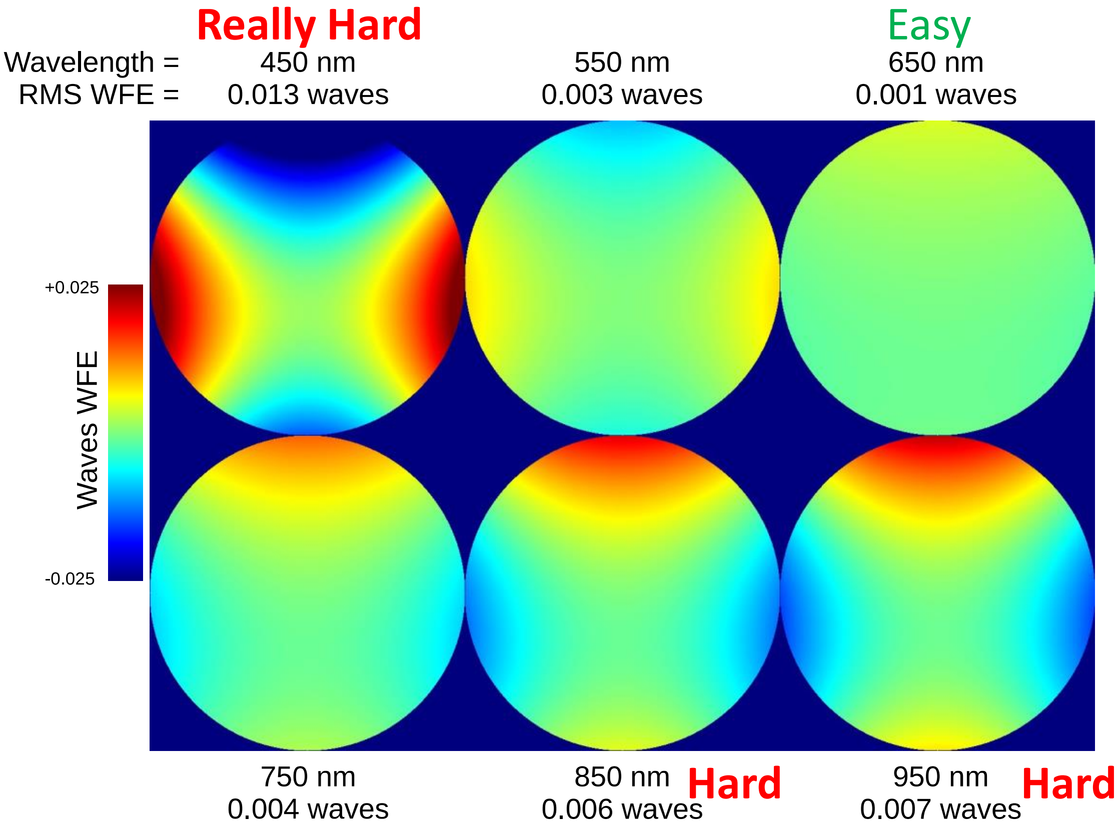
- Look for highest yield designs.
- Learn why some planets are missed, and adjust design strategy to get them.

Optimization code modifications

Polarization-Induced Aberrations

➢ **The polarization from the primary mirror is a MAJOR design constraint.**

Cycle 6 Polarization: WFE_Y-WFE_X



This figure was already cleared in John Krist's presentation "Digging A Dark Hole: Models" *in April 2016.*

- <u>Differential polarization is mostly **astigmatism**</u>
  - Negligible near 600nm → **HLC**
  - Huge WFE far from 600nm → **SPC, or HLC+polarizer**
- Huge influence on our operational modes

HLC Sensitivities

Note: *Band 1 moved to 508nm for less telescope polarization.*

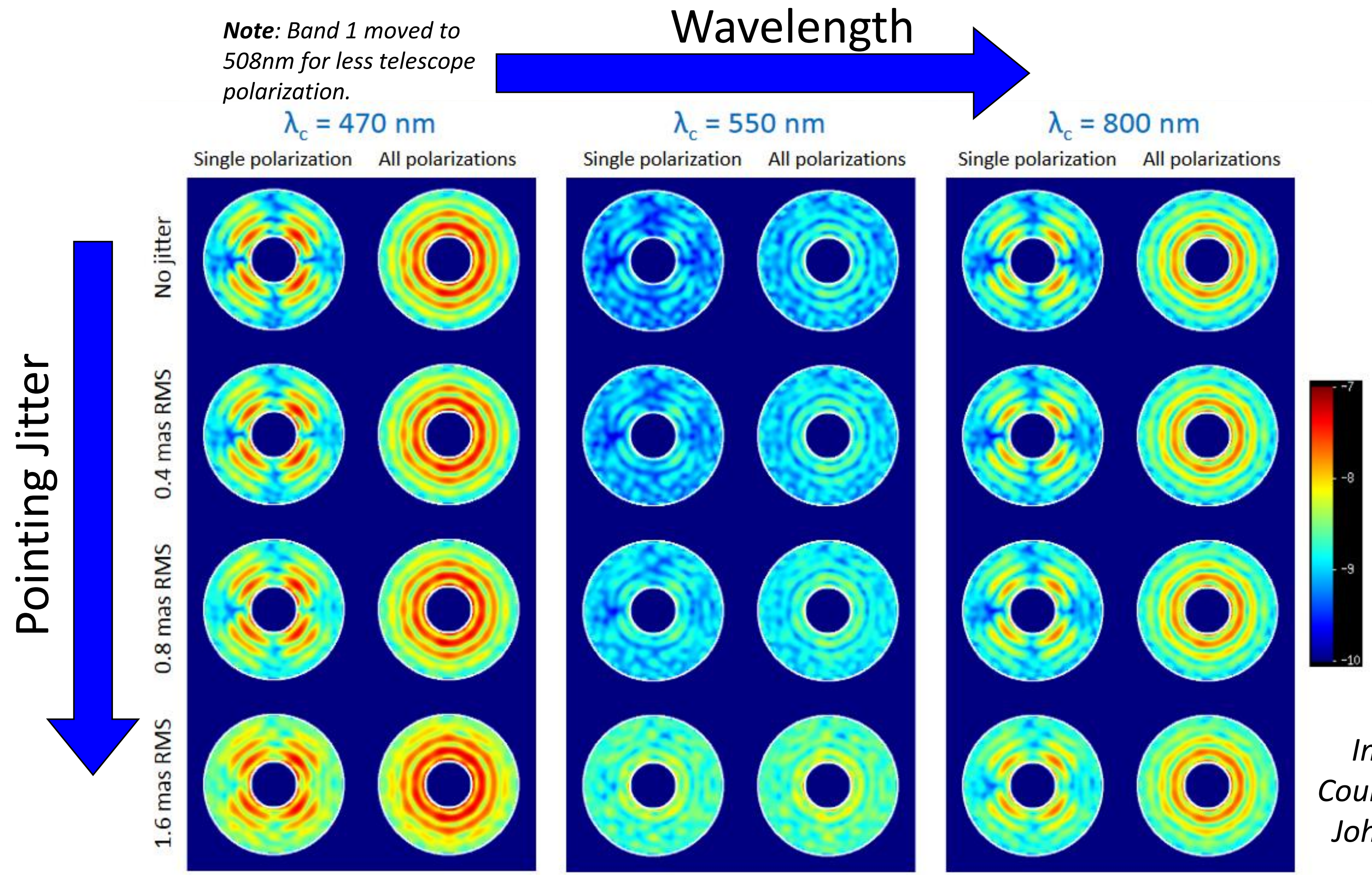


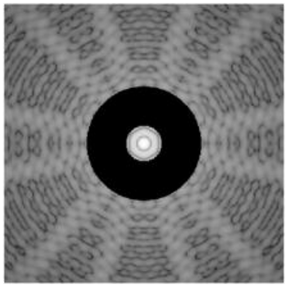
Image Courtesy of John Krist

This figure was already cleared in Feng Zhao's presentation "WFIRST Coronagraph Polarization Update – 11th Stanford Meeting" *in March 2017.*

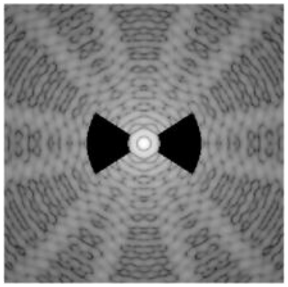
- **Outside V-band, HLC better with analyzer.**
- Analyzer helps, but pol. cross-term still degrades contrast

Summary of Modes

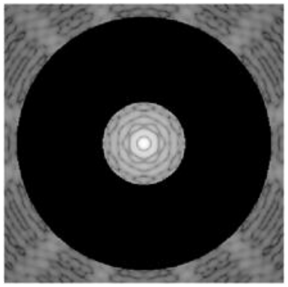
- To overcome **pupil obscurations** and **aberration sensitivities** and to **achieve science goals**, need **3 types of operating modes**:



1. **Hybrid Lyot Coronagraph (HLC)**: *exoplanet & disk imaging*
   - Full 360° FOV
   - Small IWA
   - Fewest masks (= lower complexity & cost)



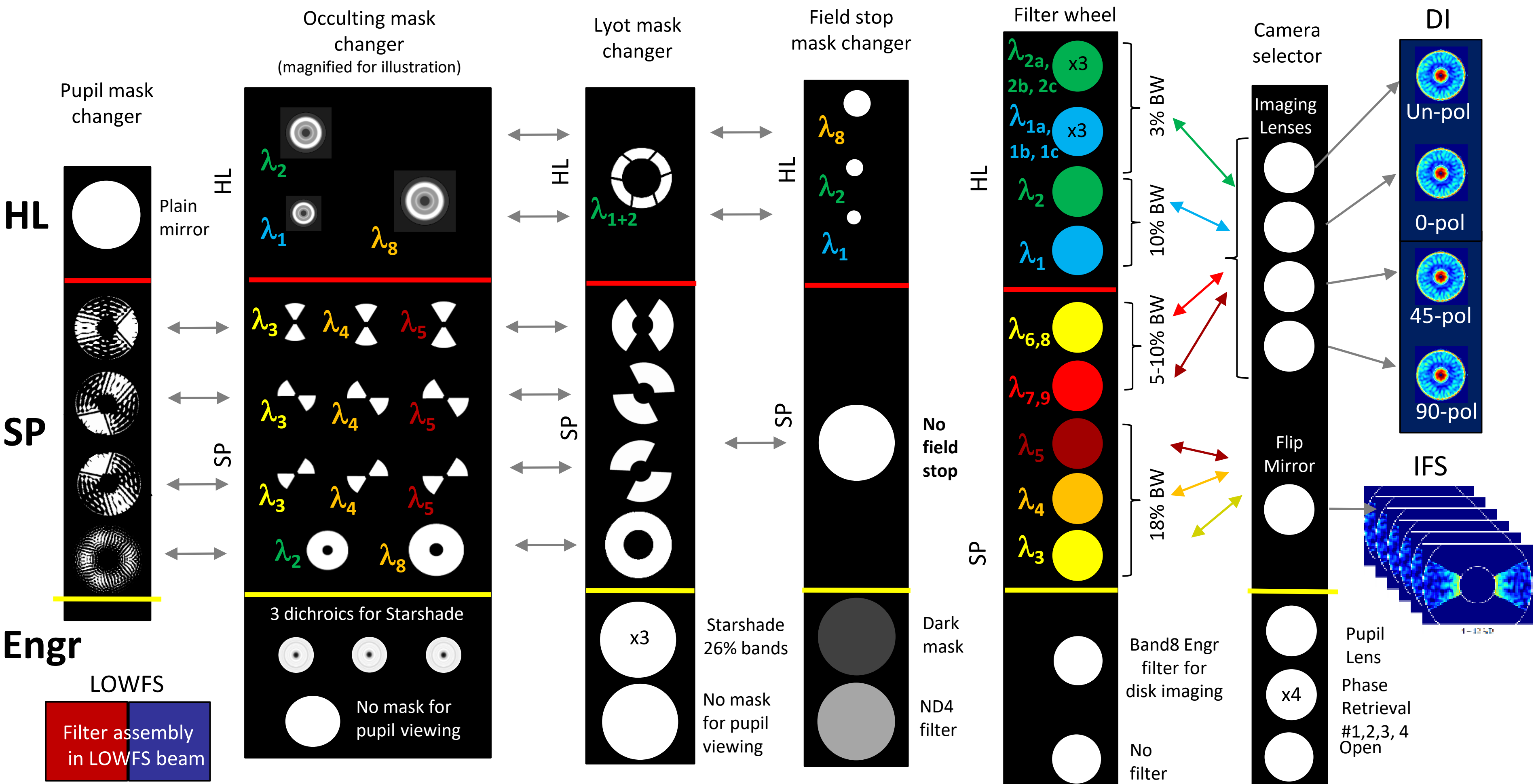
2. **Shaped Pupil Coronagraph (SPC)** for IFS: *exoplanet spectroscopy*
   - 18% BW (for spectra)
   - Small IWA
   - Lower aberration sensitivities



3. **Shaped Pupil Coronagraph (SPC)**: *disk imaging*
   - Full 360° FOV
   - Largest OWA

- Trauger et al. JATIS 2016
- Riggs SPIE 2014
- Zimmerman, Riggs, et al. JATIS 2016

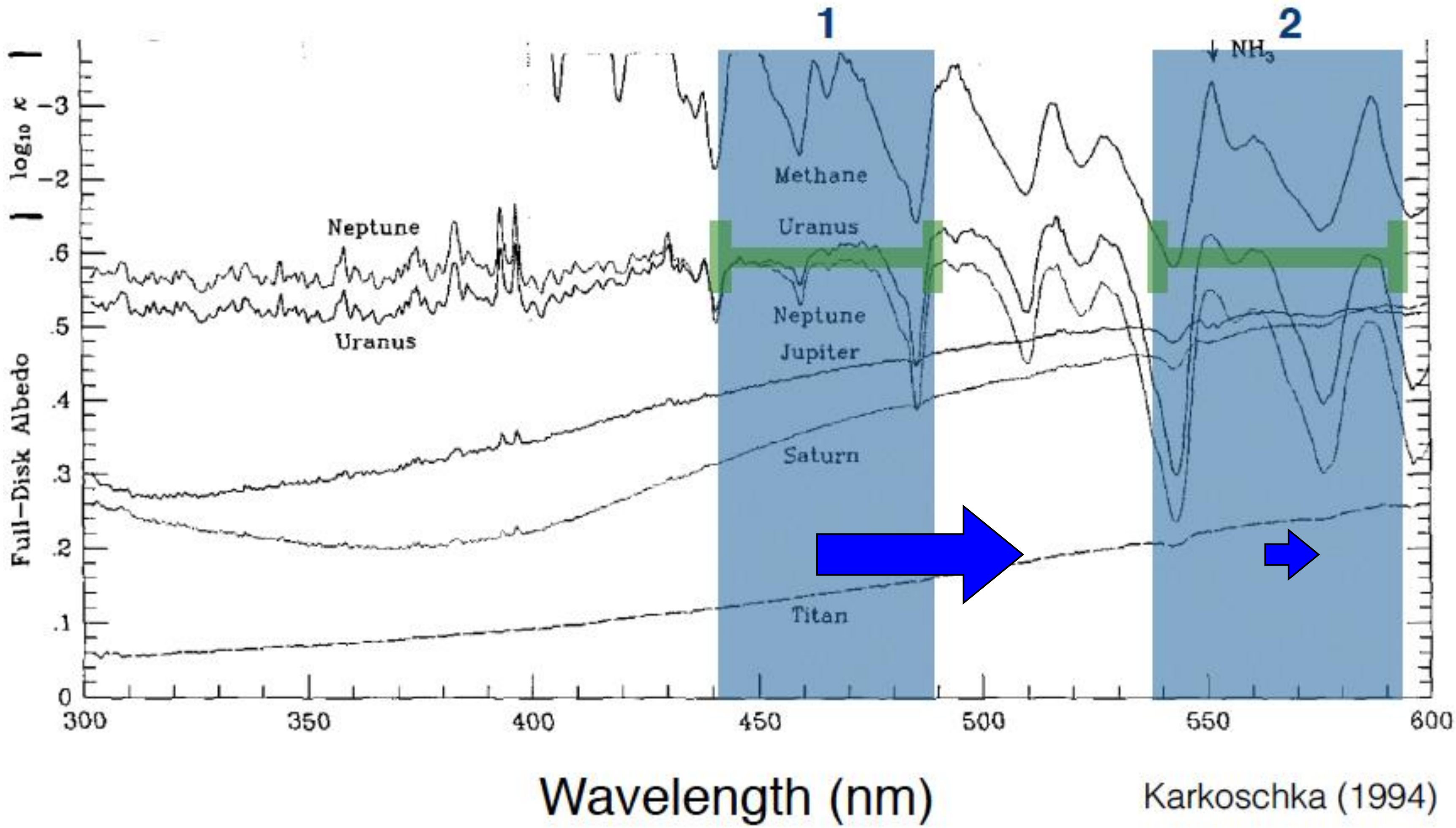
CGI Filter Wheel Populations



λ_1= 508nm λ_2=575nm λ_3=660nm λ_4=770nm λ_5=890nm

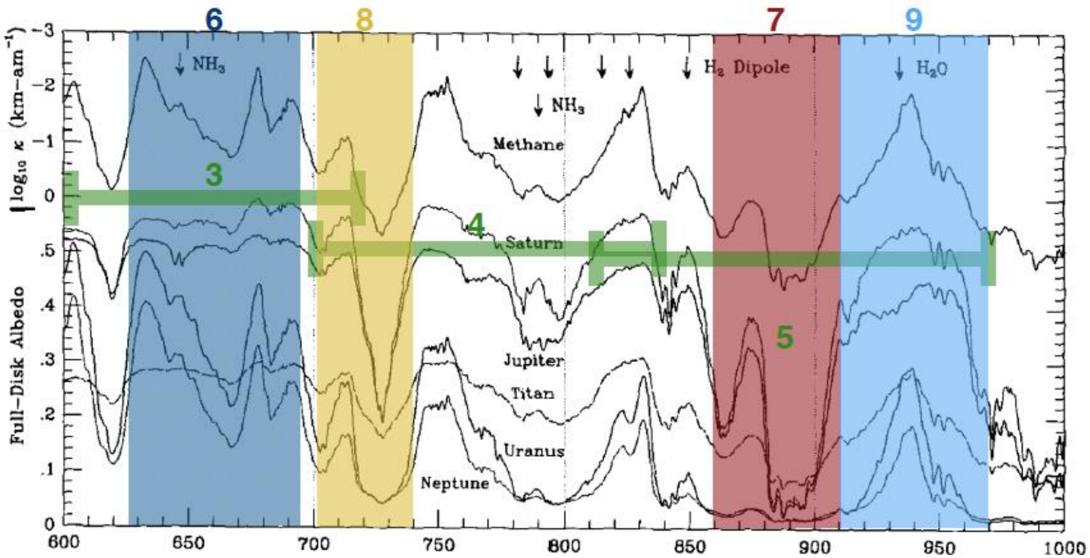
λ_{1a}= 491nm λ_{1c}= 524nm λ_{2a}=555nm λ_{2b}=594nm λ_6=661nm λ_8=721nm λ_7=883nm λ_9=950nm

CGI Science Bands 1 and 2



- Bands 1 & 2 shifted to longer wavelength because polarization WFE is too strong at B-band.

CGI Science Bands



NOTE: No polarizers or field stops in IFS channel.

CGI Bands	λ_{center} (nm)	BW	Science Purpose	Imager or IFS	Coronagraph Type	Can Use Polarizer (for Science)	*Must* Use Polarizer (for Aberrations)
1	508	10%	continuum, Rayleigh	Imager	HLC	X	X (HLC)
2	575	10%	continuum, Rayleigh	Imager	HLC	X	
3	660	18%	CH4 spectrum	IFS	SPC		
4	770	18%	CH4 spectrum	IFS	SPC		
5	890	18%	CH4 spectrum	IFS	SPC		
6	661	10%	CH4, continuum	Imager	SPC	X	
7	883	5%	CH4, absorption	Imager	SPC	X	
8	721	5%	CH4 quantification	Imager	SPC (& HLC?)	X	X (HLC)
9	950	6%	water detection	Imager	SPC	X	